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HOMOGENEOUS AEROSOL GENERATORS

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Homogeneous Aerosol Generators

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I. Summary

Two aerosol generators capable of generating essentially homogeneous, monodisperse, spherical, and electrically neutral solid particles of dye have been developed. These are an atomizer-impactor combination theoretically capable of generating particles ranging in mass median size from 0.02 to 0.5 microns, and a spinning disk generator capable of generating particles from about 0.5 to 20 microns in size.

Research during the development of these generators has shown that under many conditions of operation the particles produced are electrically charged to a substantial fraction of the maximum equilibrium charge. This charge is neutralized by a unique ion generator which reduces the charge to a few percent of the maximum.

The generators were developed using methylene blue in water or in ethyl alcohol. However, due to the many advantages of fluorescent aerosols, an effort is being made to adapt the generators to make satisfactory fluorescent particles. Satisfactory particles are now being generated from a mixture of methylene blue and commercial uranine dissolved in alcohol.

The sensitivity of modern fluorescent measuring techniques is great enough so that these aerosol generators may be used to accurately evaluate gas cleaners at airflows of several thousand cubic feet per minute and efficiencies of 99.9% or greater.

II. Introduction

An invaluable tool in aerosol and gas cleaning research is the homogeneous aerosol generator. Precise definition of experimental conditions is greatly facilitated if the test aerosols used are homogeneous, monodisperse, spherical and uniform in all characteristics.

The work of numerous investigators has shown that designing, constructing and operating such generators is no simple task. This report describes the development of two types of generators which are being used successfully at the University of Minnesota in various research programs. Although both generators are based on previous work by others, they incorporate several features which are believed essential to their successful operation.

A. Methods for Generating Homogeneous Aerosols

The principal methods by which homogeneous aerosols may be generated are described briefly as a background to the discussion of our work with the spinning disk and atomizer-impactor. These methods are discussed more in detail by Greene and Lane (1).

1. Condensation generators - Homogeneous liquid droplets, or under some conditions, solid particles, may be produced by the condensation of a vapor under certain circumstances. Self-nucleation or an external source of nucleation may be used. Best known of the external nucleation type of generators is the La Mer generator (2).

In its various modifications it has been used to produce aerosols over the range of sizes from about 0.02 to over 30 microns.

Homogeneous aerosols may also be produced by the self-nucleation which occurs when a hot saturated vapor is mixed with a cool dry gas stream. This was studied by Langmuir (3), and the basic principals widely used in the familiar DOP generator. Experience has shown that although a range of particle sizes can theoretically be generated by condensation, in practice only a limited range of sizes and concentrations are possible with a given generator. Also the liquids which are the easiest to generate are not always the easiest to sample and evaluate.

2. Atomization of a liquid suspension of solid particles - Homogeneous aerosols may be generated by the atomization of dilute suspensions of homogeneous solid particles. Monodisperse polystyrene latexes provided by the Dow Chemical Company have been used by a number of investigators (4, 5, 6). This technique has also been used to generate very small homogeneous biological aerosols (7).

Although this is a simple and reliable technique if the proper homogeneous particle suspension is available, preparation of the particle suspension and evaluation of the aerosol is often difficult. Nevertheless, this is the only procedure by which homogeneous aerosols of many materials can be prepared.

3. Atomization of liquid solutions - Solid particles may be produced by the evaporation of liquid droplets of a dilute solution. A variety of atomizing methods have been used to produce relatively heterogeneous aerosols. More refined atomizers have been combined

with impacting surfaces to obtain finer aerosols having narrower size distributions. The spray nozzle and atomizer-impactor combinations have the advantage of simplicity of construction and operation even though the aerosols are not strictly homogeneous. Spinning disk spray generators have been used to produce homogeneous particles although they are more difficult to construct and operate.

B. Factors Governing the Choice of Homogeneous Aerosol Generators at the University of Minnesota

1. Aerosol quality - Homogeneous, monodisperse, and electrically neutral solid aerosols preferably of spherical shape were desired.

2. Size range - Original size range desired was from 0.1 to 10 microns. This desired range has since been extended to 0.02 to 20 microns.

3. Aerosol quantity - A sufficient quantity of aerosol was desired so that air cleaners with flow rates to 3000 c.f.m. and with efficiencies to 99.9% could be tested with runs of less than half a day. Since this objective would be difficult to attain with differential aerosol sampling techniques such as the light scattering penetrometers, it was early decided to use integral sampling methods. Although not as convenient for routine work on small samples of filter media, integral methods are much more practical for applications where large air flows are encountered.

4. Generator cost and complexity - It was desired to keep the cost of the complete generating equipment under $2,000. This criteria alone practically eliminated the condensation generators.

III. Atomizer-Impactor Aerosol Generator

A. Introduction

Since it is difficult to generate solid particles below 0.5 microns with the spinning disk generator, the atomizer was investigated as a means of generating smaller aerosols. The generation of nearly homogeneous aerosols with the atomizer-impactor is accomplished by removing all droplets just above the lower size limit (Figure 1) leaving the relatively homogeneous remainder.

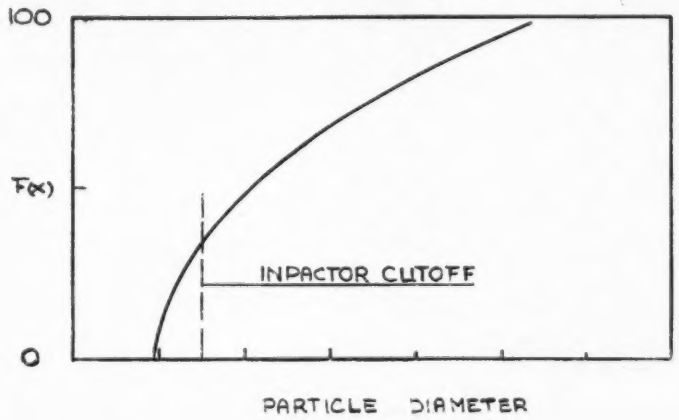


Figure 1 Impactor cutoff of atomizer size distribution

These remaining small droplets can be considered homogeneous for most experimental purposes. The droplet size at which the knee in the droplet size distribution curve occurs depends upon the severity of the atomizer action and is apparently proportional to the square root of the liquid surface tension. Therefore only a limited range of homogeneous droplet sizes can be generated by this means. It is

possible however, to generate about a 10 to 1 range of solid particle sizes by varying the solute concentrations.

Atomizers and atomizers in combination with some type of inertial impactor have been widely used for generating aerosols (10, 11, 12, 13, 14). These devices have usually taken the form of a glass atomizer in series with a simple impactor, the latter usually consisting of bent glass tubing or other glass elements. Aerosols may be generated with these devices by the following methods:

a. A non-volatile liquid may be atomized to give an aerosol consisting of liquid droplets.

b. A solute dissolved in a volatile solvent may be used to produce solid particles through evaporation (10, 11, 12, 13, 14).

c. Particles of the desired size may be suspended in a volatile liquid in which case evaporation of the solvent leaves the solid particles essentially monodispersed providing the initial concentration is low enough (6, 7).

While the glass atomizer-impactor combinations described above have been quite satisfactory when calibrated, the objective was to design a device which could be reproduced precisely. Hence, the all-metal Collison atomizer (1, 11, 13) was selected and an impactor of machined metal was designed rather than an all glass device. Although the initial cost of the apparatus described here is greater, the performance is somewhat better and the device can be duplicated precisely from the drawings.

This apparatus differs in one respect from most atomizer-impactor aerosol generators in that it includes means for neutralizing

the electric charge on the particles. Neutralizing the aerosol has been found necessary in making this generator perform satisfactorily.

The impactor has been designed so that its cutoff size can be varied somewhat by changing the impactor orifice plate. With the orifice plate shown in Figure 3 the droplet cutoff size is approximately 2 microns, yielding an upper solid particle size limit of approximately ~~0.2~~ 0.4 microns when using a 1% by volume solute concentration. Although it is theoretically possible to generate aerosols having an m.m.d. (mass median diameter) from 0.02 to 0.5 microns, only a few sizes have been calibrated adequately due to the lack of suitable sampling methods. Further calibration work is planned.

B. Apparatus Description

A schematic of the complete aerosol generator is shown in Figure 2. It consists of a standard Collison atomizer (1, 13), a specially designed impactor, a high output ion generator (9), a mixing tee and an aerosol holding chamber. The components are discussed below.

1. Collison atomizer - The Collison atomizer was chosen as a source of fine droplets because it can be duplicated exactly, has a built-in impactor stage which eliminates most drops over 10 microns in size and has relatively high aerosol output. Working drawings may be obtained from the British Standards Institute (13). The atomizer requires approximately ~~0.4~~ 0.3 cfm of oil-free air at 30 psig.

With water as the solvent, the generator may be operated for several hours without significant change in aerosol particle size. However, when more volatile solvents such as alcohol are used, the

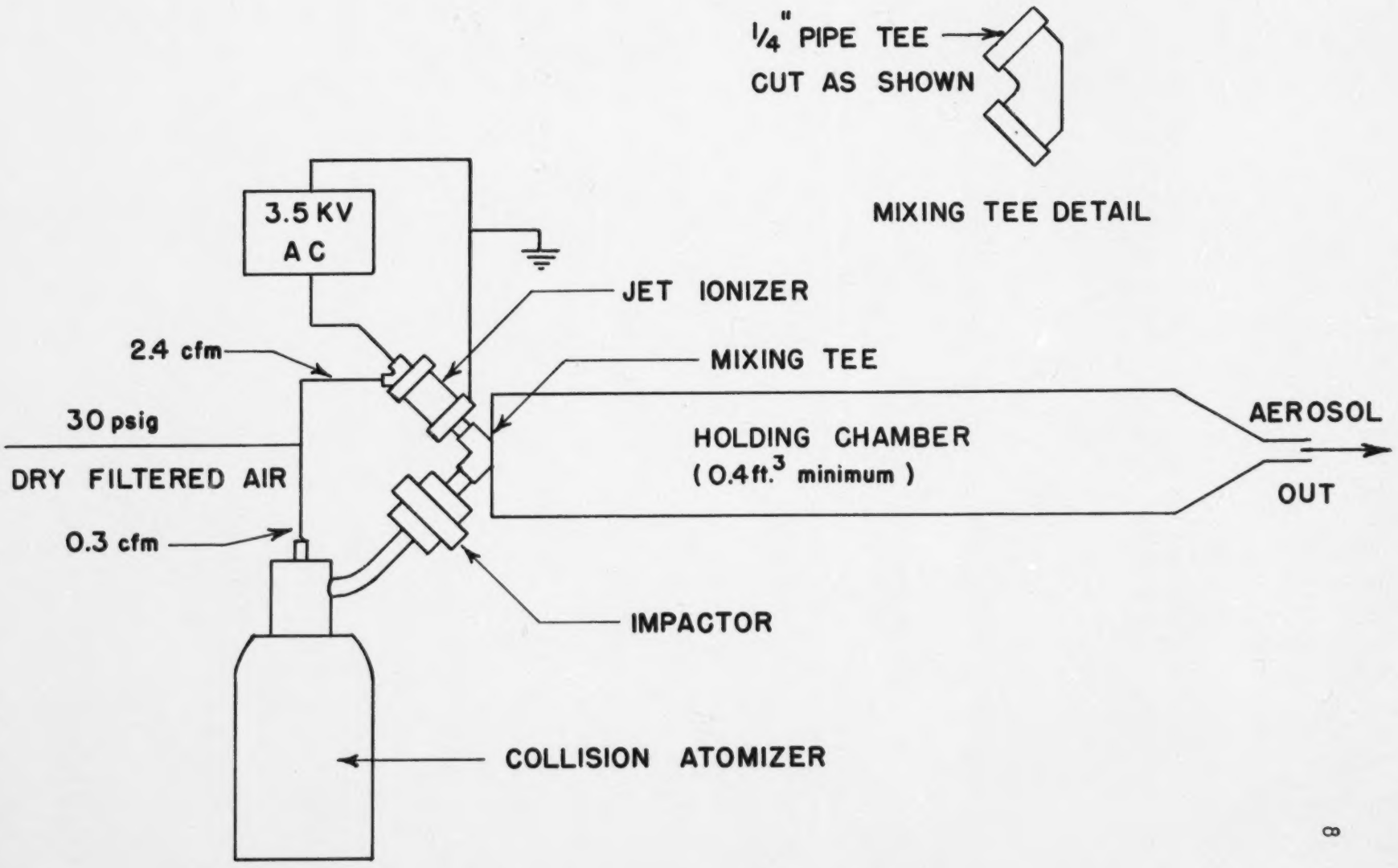


Figure 2. Atomizer-impactor aerosol generator

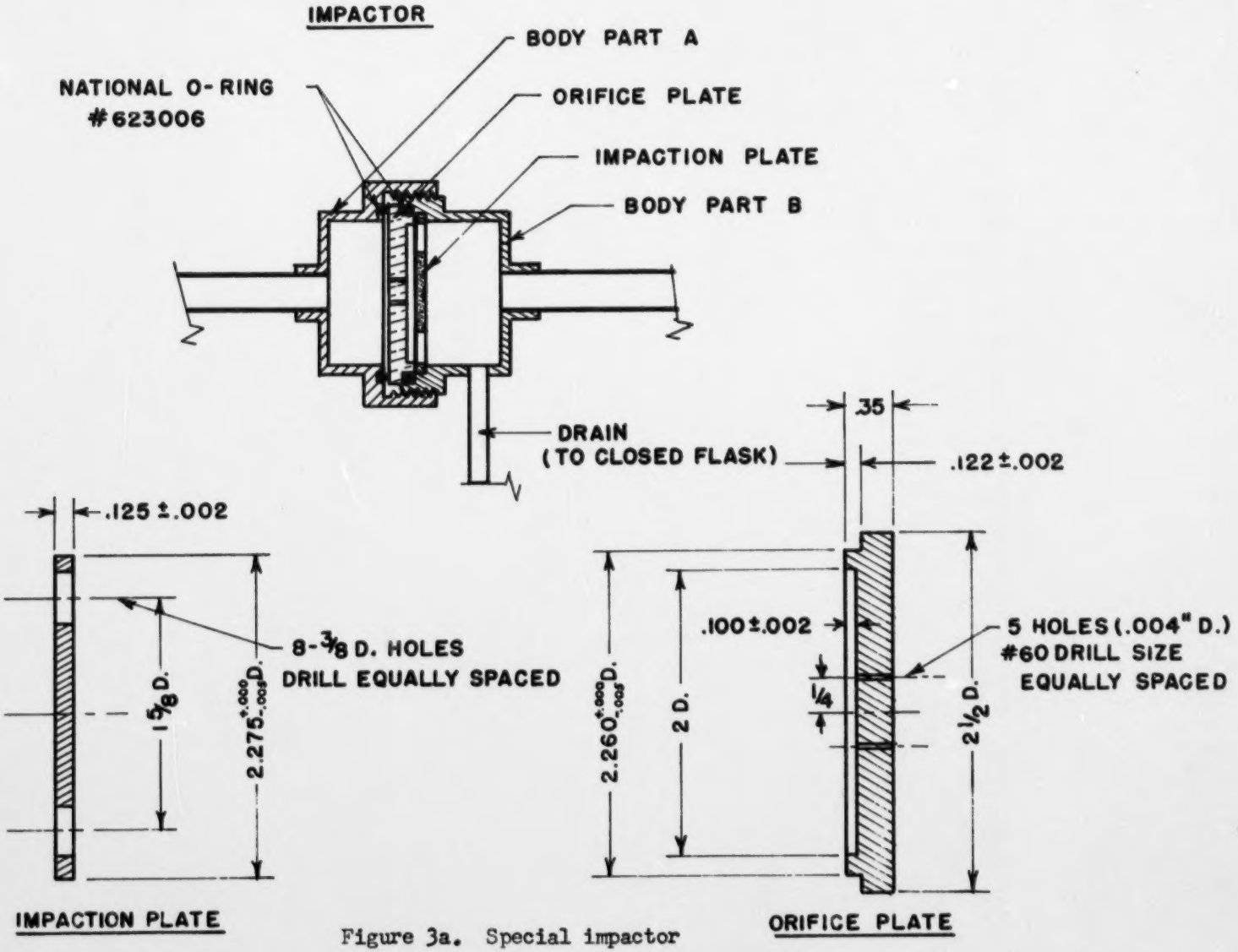


Figure 3a. Special impactor

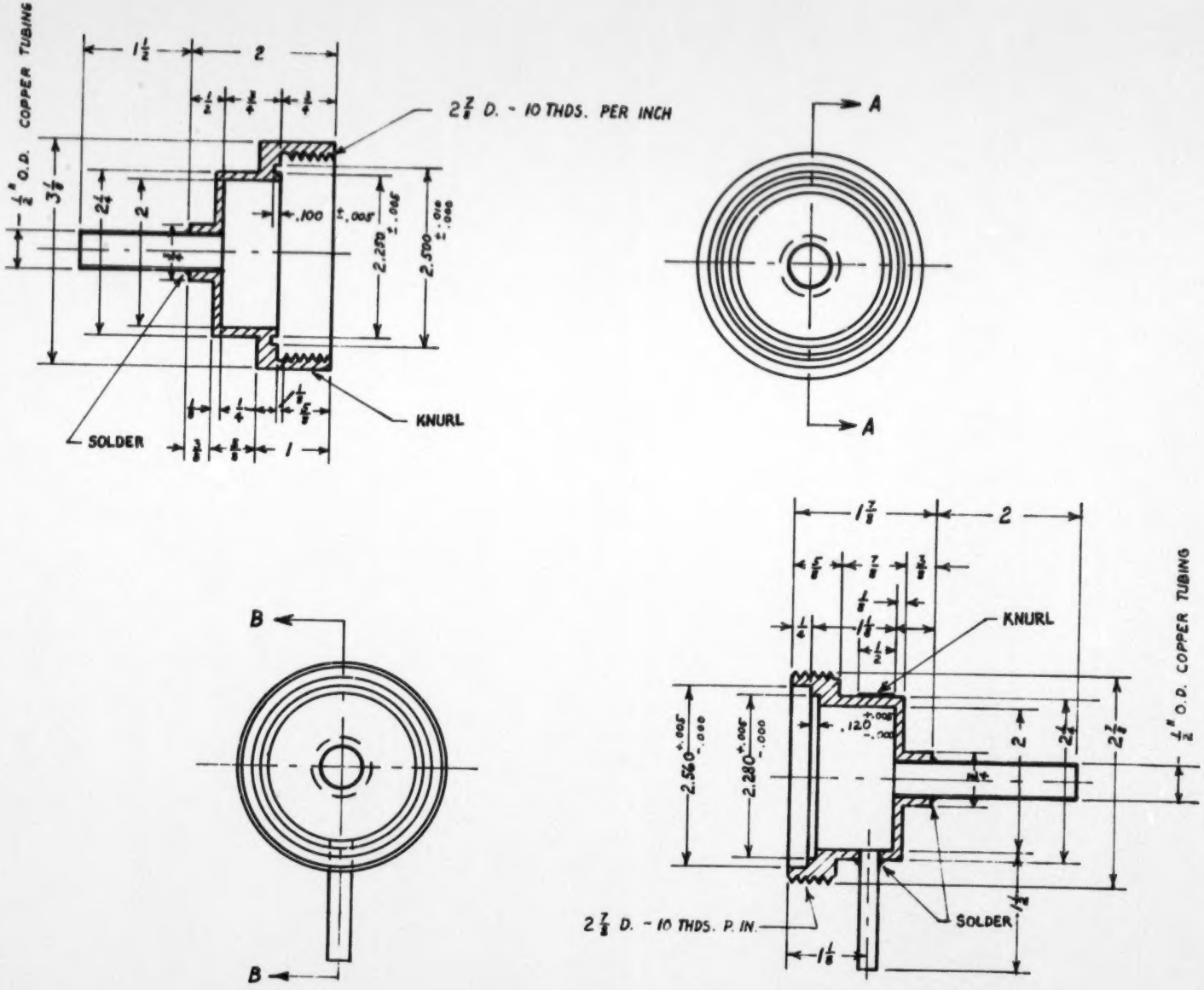


Figure 3b. Special impactor

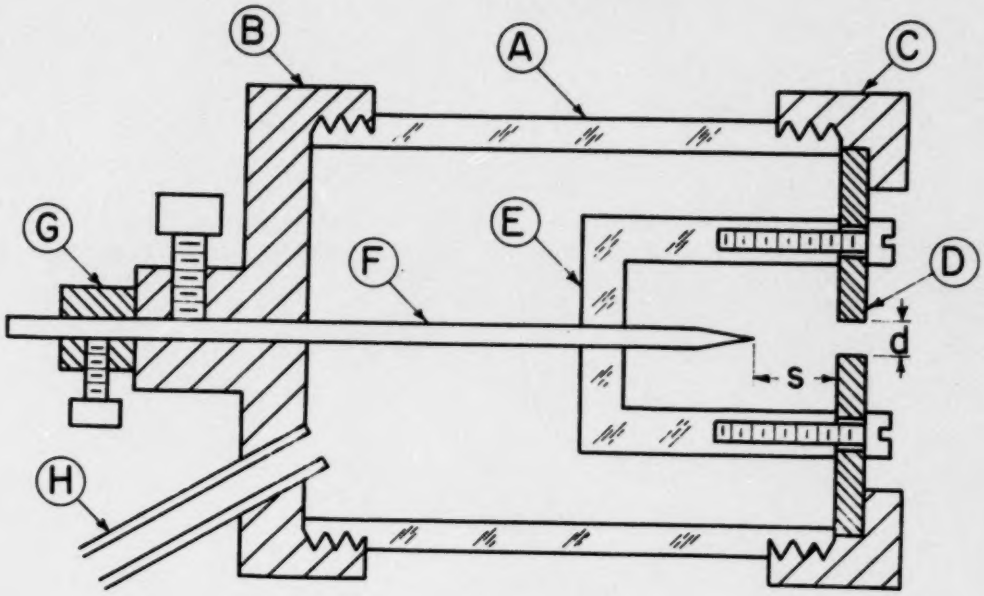
solution in the reservoir must be added to or changed every 20 to 30 minutes. Either a much larger reservoir or a continuous feed system should be used for volatile solvents. Foaming has been encountered under some conditions but has not been a serious problem.

2. Impactor - The special impactor is shown in Figure 3a and 3b. It has been designed to operate with the standard Collison atomizer and to incorporate removable impactor plates so that the cutoff size may be varied. The impactor plate used has a cutoff size of 2 microns.

3. Ion generator - To neutralize the electrical charge on the evaporating droplets it is necessary to rapidly mix the aerosol with a high concentration of mixed positive and negative small ions. These ions are generated by a sonic jet ion generator described in (9). A schematic of the ion generator is shown in Figure 4.

As operated in conjunction with the atomizer-impactor aerosol generator and the spinning disk generator, a 1/16 orifice is used--the spacing S shown on the drawing is maintained at approximately 1/8 inch, 3.5 kilovolts A.C. on the needle is used and the pressure in the chamber is maintained at 30 lbs. per square inch gage. The needle must be kept sharp; a needle tip diameter on the order of 20 microns will assure high ion output.

The operating conditions given above produce an adequate concentration of ions for the aerosol neutralization. Higher concentrations of ions can be produced by moving the needle closer to the orifice, increasing the air pressure and operating at somewhat higher currents. At the stated conditions the total ion output is



d — Orifice diameter
s — Needle spacing
A — Lucite tube
B — End cap
C — End cap
D — Orifice plate
E — Needle positioning bracket
F — Needle
G — Needle stop
H — Air connection

Figure 4. Ionizer

about 10^{13} ions per second, and the concentration in the aerosol mixing zone is about 10^{10} ions/c.c.

A small high voltage A-C transformer that will deliver 100 microamps at 3500 volts is a satisfactory power source for the ionizer.

Compressed air to the ionizer should be dry, filtered and oil-free.

4. Mixing tee - Since rapid mixing of the droplets with the ions is vital, the mixing tee arrangement shown in Figure 2 should be adhered to. The distance between the ion generator, the impactor and the mixing tee should be as short as possible.

5. Holding chamber - Aerosol from the atomizer-impactor and ions from the ionizer are discharged through the mixing tee into a holding chamber as shown in Figure 2. By experiment it was determined that a minimum residence time of about 4 seconds was necessary for charge neutralization.

C. Experimental

1. Aerosol sampling - Aerosol sampling has been by membrane filters or by the low pressure impactor technique suggested by General Mills (7). Membrane filters have been used to sample particles for evaluation by light microscope if the aerosol size is not too small. Attempts will be made to measure particle size from electron photomicrographs of carbon replicas made from membrane filters.

The low pressure impactor sampling train is shown in Figure 5. This device can be used to sample aerosols of 0.1 micron median size

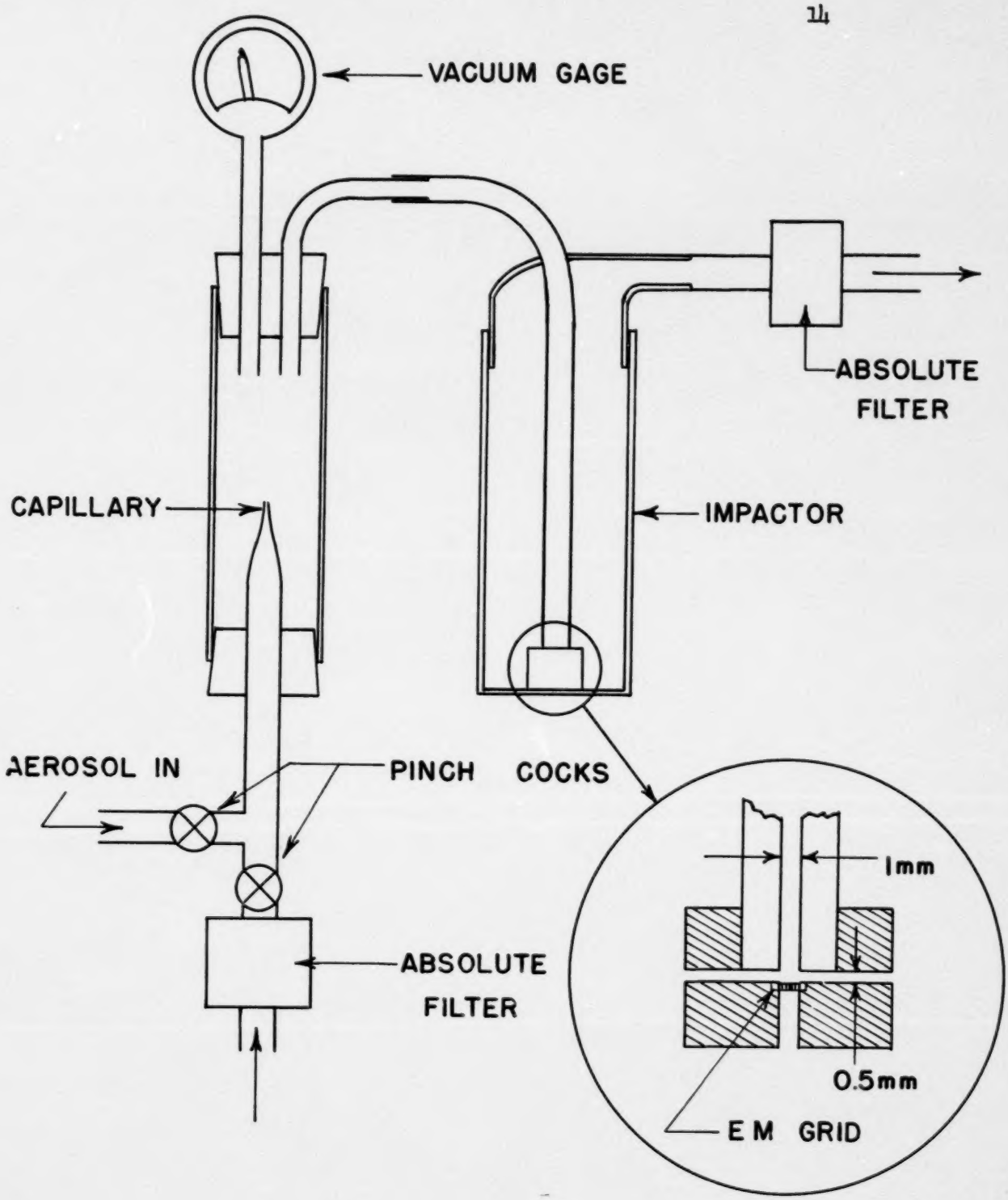


Figure 5. Impactor sampling train

because, at pressures in the impactor of 1 in Hg absolute or less, the increase in the Cunningham slip term reduces cutoff size of the impactor to below 0.1 micron. Absolute pressure required to obtain 50% impactor collection efficiency is shown in Figure 6. In practice the after filter (Figure 5) was used to determine the actual efficiency of the impactor for each sampling condition used. At an absolute pressure of 1.6 in Hg absolute, the impactor had a weight efficiency of about 85% when sampling the nominal 0.17 micron aerosol (Figure 7).

The chief virtues of the low pressure impactor are its simplicity and ability to concentrate the sample directly onto an electron microscope grid. Its chief deficiencies are its rapid dropoff in efficiency below 0.05 micron and the apparent agglomeration which it causes in the deposit on the electron microscope grid.

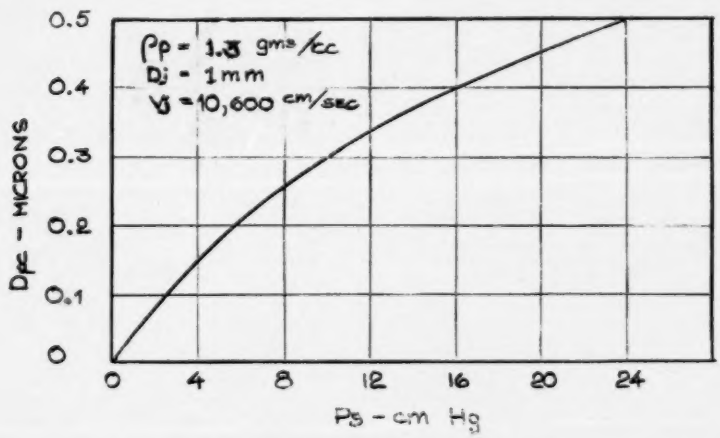


Figure 6 Absolute pressure in impactor to obtain 50% collection efficiency at given particle size.

Improved sampling and aerosol evaluation techniques now being investigated include a thermal precipitator and a carbon film replica technique

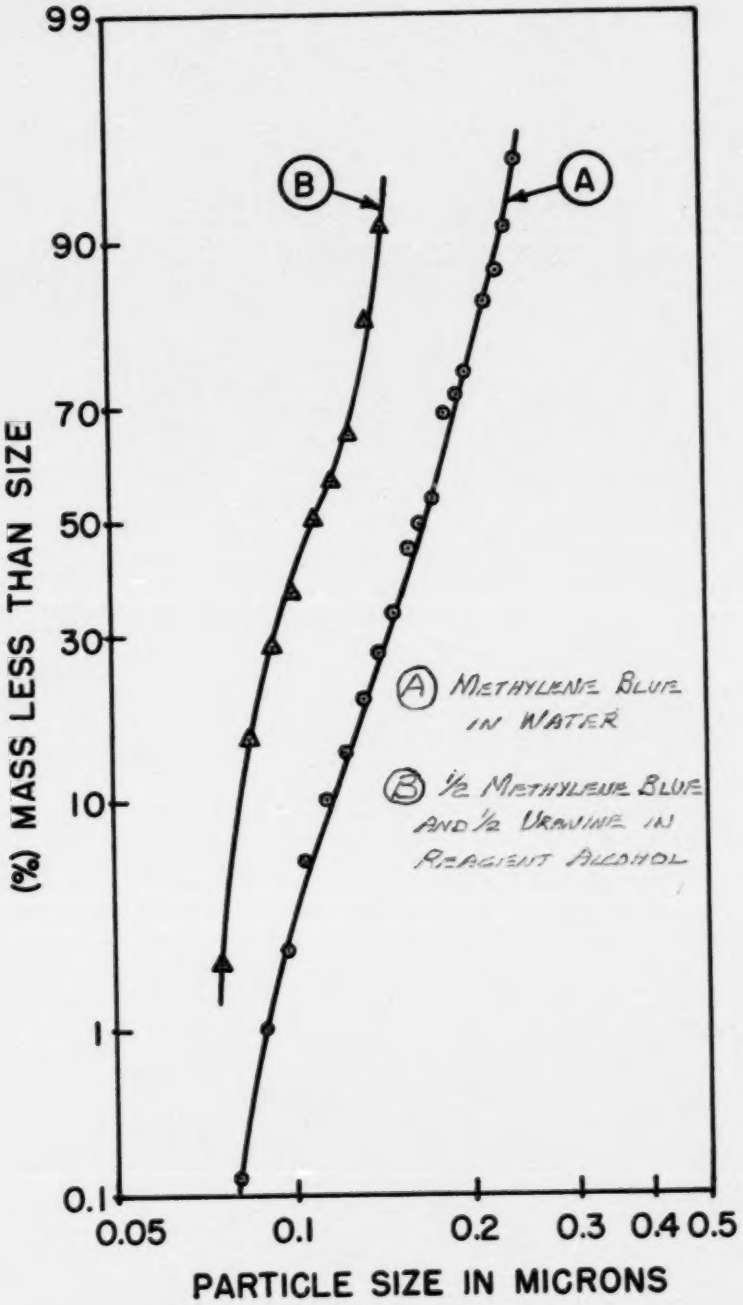


Figure 7. Particle size distribution of methylene blue aerosol

2. Aerosol particle size calibration - The particle size distribution of an aerosol generated using 1.38% by weight methylene blue in water is shown in Figure 7. The distribution was determined by measuring several hundred particles from electron photomicrographs of impactor collected samples. Due to the limitations of the impactor sampler, the m.m.d. of smaller particle sizes were calculated from Figure 8.

Comparisons of the actual size with the calculated size of methylene blue particles generated with the spinning disk, indicate that the actual size is greater than the calculated for low solute concentrations. Possible reasons are mentioned later in the report. It is estimated that the actual size may be as much as 50% greater than the calculated size for solute concentrations of 10^{-5} parts by weight. Thus the size-concentration curve of Figure 8 should be considered as tentative until direct measurement of the smaller sizes has been made.

3. Solute and solvent combinations - Most of the work to date has been done using methylene blue dissolved in water since this combination produced spherical, dry particles at normal humidities and temperatures. Although the generator will produce several times as much aerosol if alcohol is used as the solvent, the resulting aerosol particles are non-solid and smeared when sampled with the impactor.

More recent attempts to generate fluorescent aerosols have shown that the production of solid particles at normal humidities and temperatures is not an easy task. The degree of success obtained with various solutes and solvents is summarized in Table I.

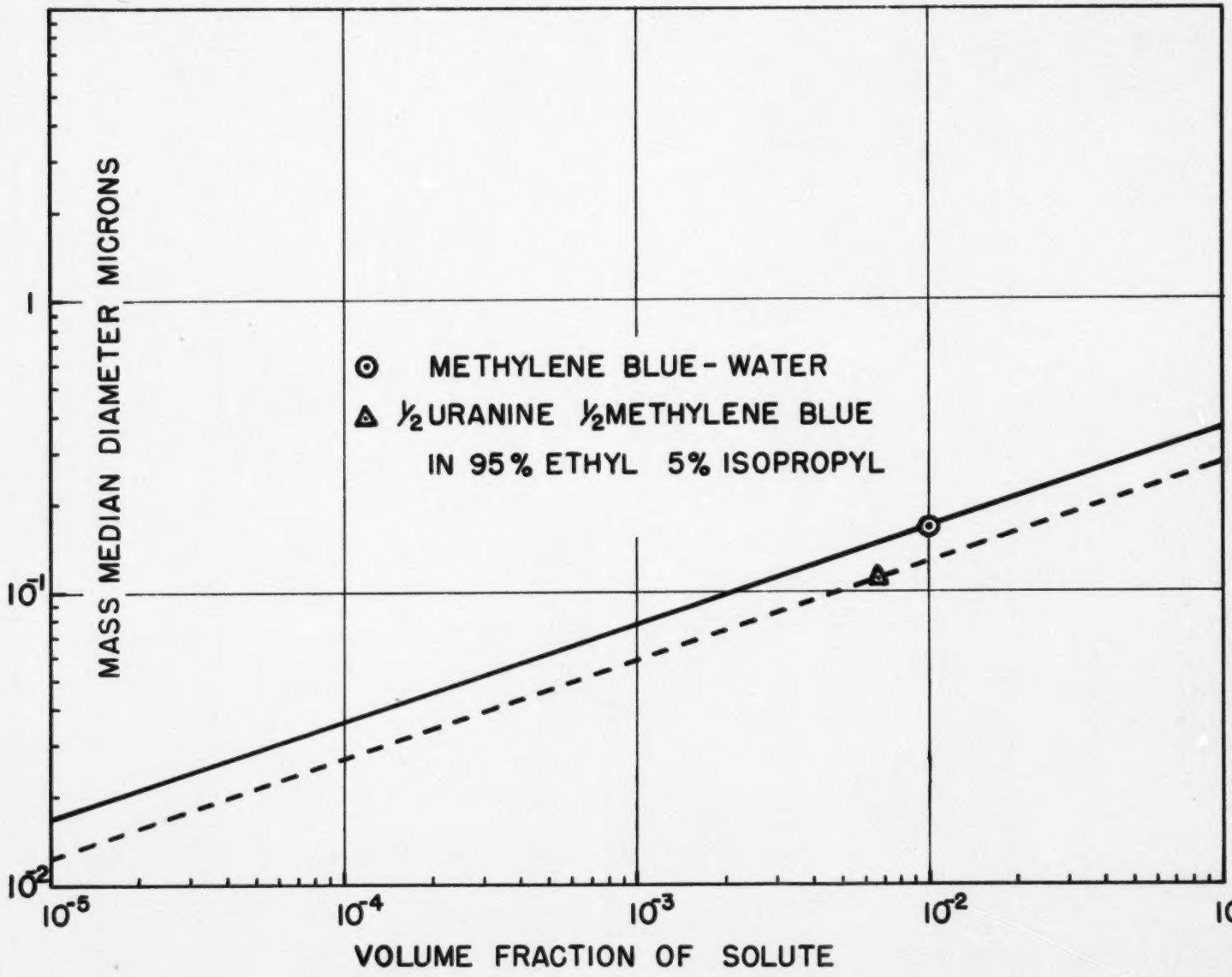


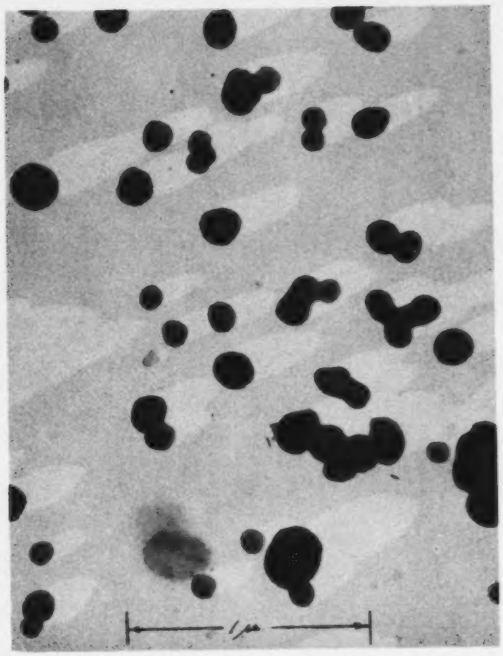
Figure 8. Particle size - solute concentration for the impactor-atomizer aerosol generator

Table I. Observations on electron photomicrographs of aerosol particles sampled with impactor.

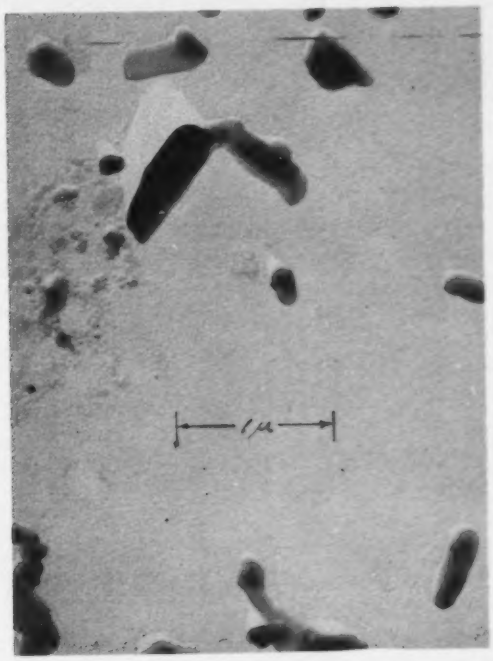
Solvent	Solute		
	Methylene Blue[a]	Uranine[a]	½ Methylene Blue ½ Uranine
Demineralized water	Good, solid particles	Wet particles	Foamed, fair. Some smeared particles.
95% Ethyl Alcohol + 5% Methyl Alcohol	Smeared. Wet particles		
95% Ethyl Alcohol + 5% Isopropyl (reagent grade)	Smeared. Soft particles	Smeared. Wet particles	Good. Solid particles
Methyl Alcohol	Smeared. Soft particles	Wet particles	Fair. Some soft particles

(a) Commercial grade

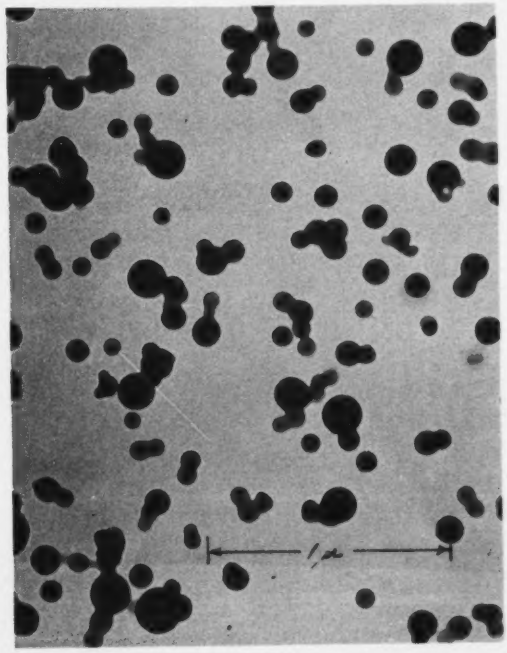
Electron microscope photomicrographs of some of the combinations given in Table I are shown in Figure 9. Uranine, being quite hydroscopic, may require artificial drying if a pure uranine aerosol is to be generated successfully. Since facilities are not available in our laboratory to dry the large volume of air required, an effort is being made to find conditions under which a satisfactory aerosol can be generated at ambient conditions. Preliminary evaluations indicate that 50% methylene blue and 50% uranine dissolved in 95% ethyl and 5% isopropyl reagent grade alcohol produces satisfactory particles at ambient conditions. The methylene blue does not interfere to any great extent with the fluorometric analysis of aerosol samples so that the advantages of the fluorescent aerosol are retained without the necessity of drying. Further research may



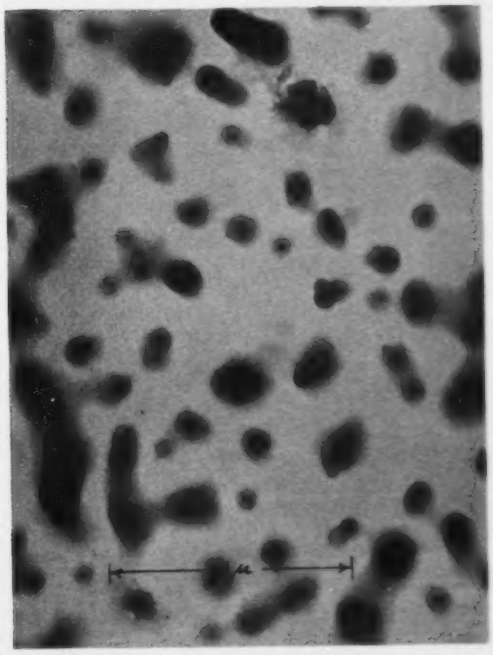
Methylene Blue in Water



Methylene Blue in Ethyl Alcohol



½ Methylene Blue and ½ Uranine in Reagent Alcohol



Uranine in Water

Figure 9. Electron microscope photomicrographs

reveal better dilutants for the uranine than methylene blue.

4. Charge neutralization - Early experiments with the atomizer-impactor and the spinning disk showed that under most operating conditions the aerosols produced carried a substantial electric charge. Practically all of the charge evaluation and aerosol neutralization work has been done with the simple device shown in Figure 10. It consists of two concentric cylinders which slip into a lucite mount which in turn is screwed into one of the samplers of the air cleaner test duct. A separating voltage of from 0 to 2000 volts is impressed between the cylinders.

If the fraction passing through the separator is designated by P then the particle charge is related to the various measurable variables by the following equations:

Assuming laminar flow:

$$q_l = \frac{3.12 \times 10^3 \, v_o \, D_p}{E} (1 - P) \qquad (1)$$

Assuming turbulent flow

$$q_t = \frac{3.12 \times 10^3 \, v_o \, D_p}{E} \ln P \qquad (2)$$

where D_p = particle size - microns

E = electric field between cylinders - volts/cm.

v_o = average velocity between cylinders - cm./sec.

q = number of electron units of charge on particle

For high values of P, q_l and q_t will be nearly equal. For this case charge estimation with this simple device is relatively independent of the flow regime.

A summary of the results of numerous charge measurements is

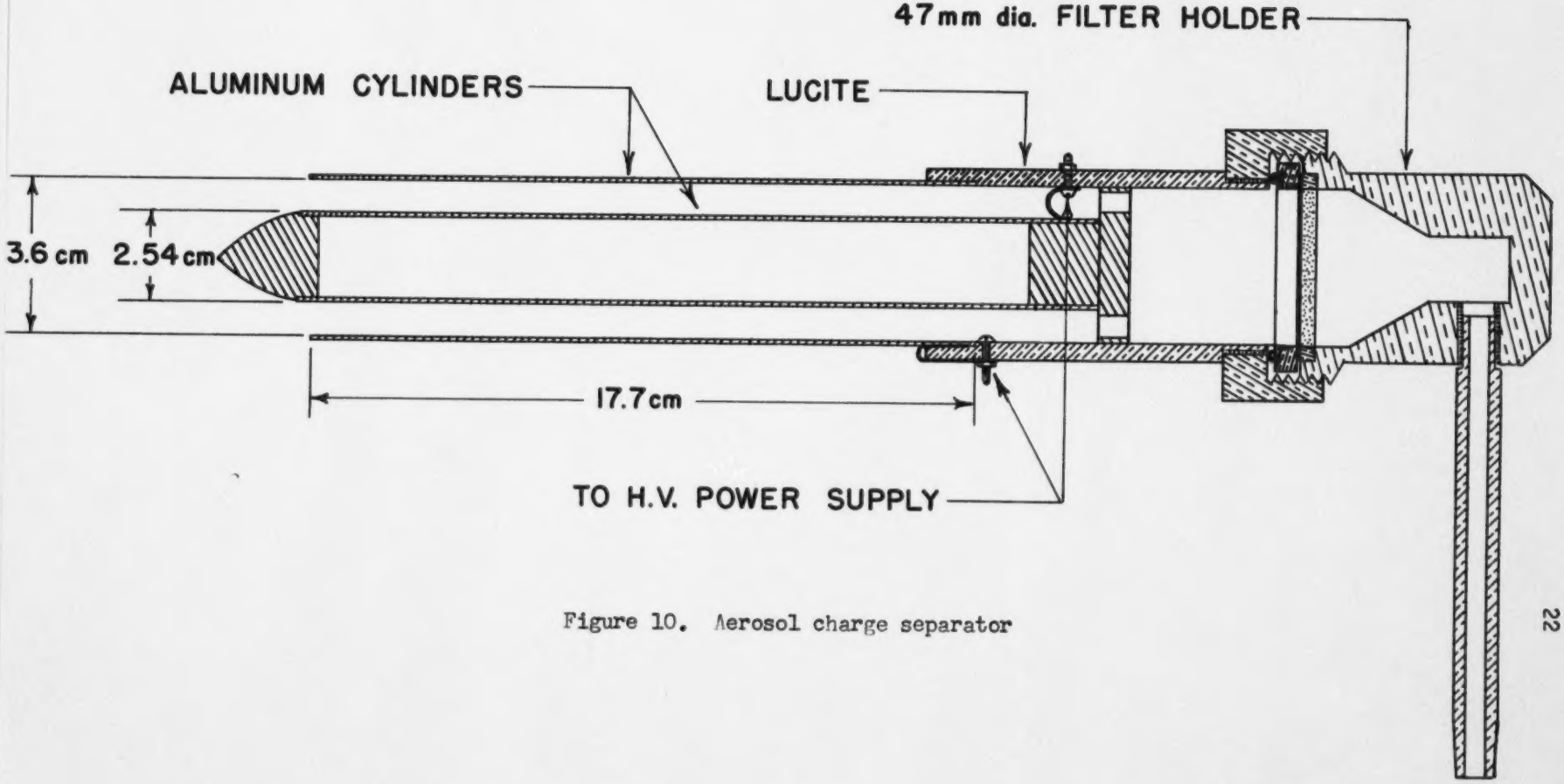


Figure 10. Aerosol charge separator

given in Table II. The un-neutralized charge on the particles is a substantial fraction of the maximum charge which such size particle can carry.

Table II. Measured charge of particles generated with the atomizer-impactor.

Solute[e]	Solvent	D_p	Charge Neutralizer	Percent Charged[a] Fraction (+)	(-)	q_t
MB	Water	0.17	off	0[d]	100	14
MB	Water	0.17	on	0[d]	100	2[c]
½MB + ½U	Alcohol[b]	0.11	off	44	56	5.8
½MB + ½U	Alcohol	0.11	on	53	47	0.85

(a) This is the percentage of charged particles that were collected on each cylinder of the collector.

(b) 95% ethyl alcohol + 5% isopropyl alcohol (reagent grade)

(c) The measurement sensitivity during these test was about $q = 2$. The actual charge was probably several times less.

(d) Approximate

(e) MB - Methylene Blue U - Uranine

IV. Spinning Disk Aerosol Generator

A. History

Walton and Prewett (15) first reported the production of homogeneous droplets by spraying a liquid from the edge of a high speed, air driven, air supported top using Beams' (17) design. They also mentioned use of an electric motor driven disk to generate large droplets together with design criteria and a range of operating conditions that had been investigated. Improvements in the design and operation of the spinning top were reported in an article by May (16). Later innovations by the Harvard Air Cleaning Laboratory (8), Battelle Memorial Institute (20) and others, involved use of a high speed air motor to drive a disk.

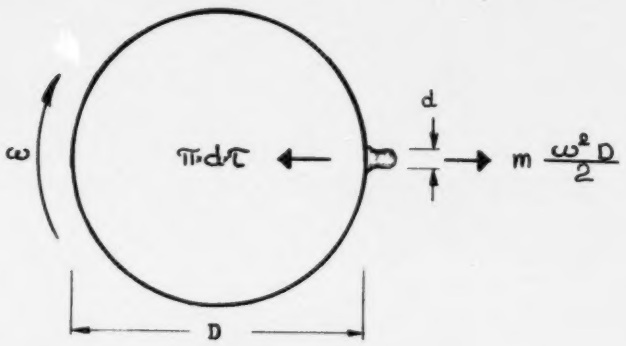
Cottrell (19) investigated several methods of producing a solid homogeneous aerosol and concluded that the spinning top appeared most promising, although difficulties in building and operating the apparatus were noted.

B. Development Objectives

The original objective in developing the spinning disk generator was to design a self-contained unit capable of producing a solid homogeneous aerosol in the size range of 0.5 to 10 microns in sufficient concentrations to enable testing air cleaning devices at airflows up to 3000 c.f.m. The size range has now been extended to 20 microns.

C. Theory and Characteristics

If liquid is fed continuously onto the center of a spinning disk at a sufficiently low rate, the resulting spray consists of droplets in two distinct size ranges. The size of the larger droplets can be calculated approximately by balancing the surface tension force against the centrifugal force acting on a droplet at the disk edge.



D = disk diameter - cm.
d = droplet diameter - cm.
ω = disk speed - rad./sec.
m = mass of droplet
ρ = liquid density - gram/cm³
τ = surface tension - dynes/cm.

Figure 11. Force balance on a droplet

$$\tau \pi d = m \frac{\omega^2 D}{2}$$

Assuming the droplet to be a sphere of diameter d

$$\tau \pi d = \frac{\pi}{6} \rho d^3 \frac{\omega^2 D}{2}$$

Solving for the droplet diameter gives

$$d = \frac{K}{\omega} \sqrt{\frac{\tau}{\rho D}} \qquad (3)$$

where K is constant.

Although equation 3 is approximate, it illustrates the relationship between the principal variables. Walton and Prewett (15) found that K varied between 2.67 and 6.55 over a range of conditions investigated. Various investigators have used spinning disks to generate droplets from ten to several thousand microns. Solid particles much smaller than 10 microns have been obtained by evaporating dilute solutions of suitable dyes.

Theoretically the particle size is proportional to the cube root of the solute concentration. However, it has been observed that the particles resulting from the evaporation of a very dilute solution are usually larger than the theoretical size. Possible explanations are the presence of non-volatile impurities and droplet charge during evaporation. There is also some evidence to indicate that the rate of droplet evaporation influences the particle shape and particle charge. Occasionally irregular shaped crystals, hollow shells, soft gelatin-like particles or odd-shaped particles have been observed. Often slight changes in the solute or solvent mixture have had a marked effect on the aerosol quality.

The smaller satellite droplets may also be used as an aerosol. When the liquid droplet detaches itself from the disk edge a thin liquid thread remains attached to both the primary droplet and the disk. At low feed rates the major portion of the liquid thread breaks up into several droplets of about one-fourth the primary drop size. Although the satellite droplets are several times as numerous as the primary droplets they contain only about 10% of the total mass. These satellite droplets are quite homogeneous at low feed rates and can also be used as a homogeneous aerosol.

Excellent high-speed photographs of the formation of drops from a spinning disk atomizer were obtained by Fraser et. al. (18). Photographs obtained by Walton and Prewett (15) show that satellite size is affected more than the primary size is by feed rate. At feed rates between 0.04 and 0.2 cm^3/sec., they found that two distinct sizes of droplets were produced. As the feed rate was increased beyond 0.2 cm^3/sec. the distinction between main and satellite droplets decreased until at a feed rate of 2.8 cm^3/sec. a heterogeneous spray was obtained with the larger droplets being approximately the same diameter as the primary droplets at low feed rates.

All droplets leave the disk edge at approximately the peripheral velocity but the satellite droplets are projected a much shorter distance due to their greater drag to mass ratio. This is illustrated in Figure 12 where the stopping distance of non-evaporating alcohol droplets in still air is shown. The initial velocity corresponds to that of a droplet leaving a 4.65 cm. diameter disk rotating at 20,000 R.P.M. From the curve it is seen that the 60 micron primary droplets generated at this condition have ten times the stopping distance of the 15 micron satellite droplets. Even though particle evaporation decreases the stopping distance of the primary droplets, and induced air from the disk increases the satellite stopping distance, separation is easily accomplished by a properly designed satellite removal system.

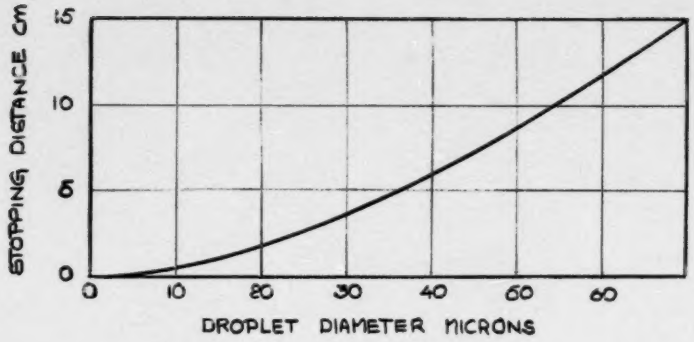


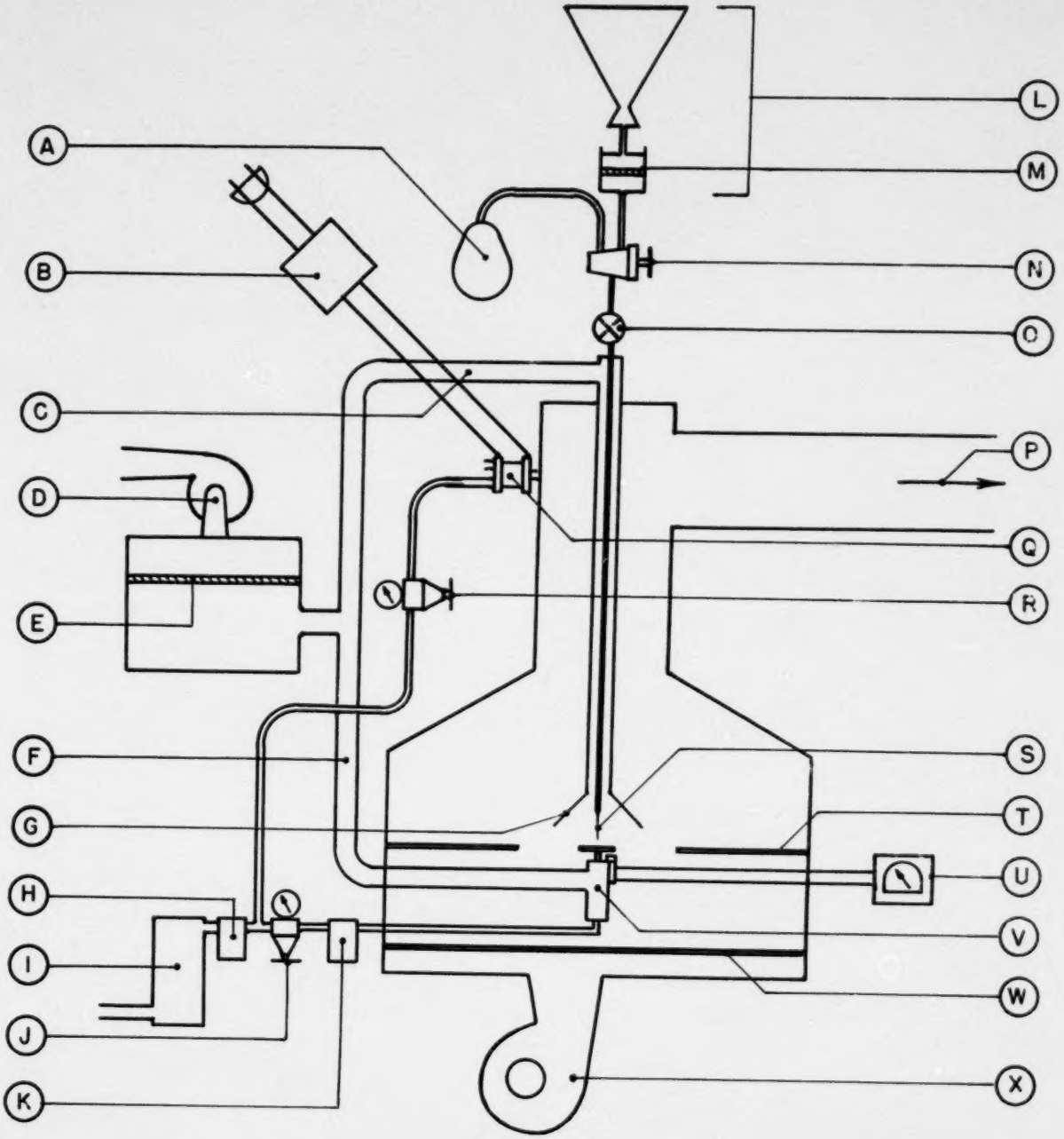
Figure 12. Stopping distance of droplets with an initial velocity of 4900 cm/sec

D. Aerosol Generator Design

Development work on the aerosol generator was begun using an Aro Model 7335-A air motor to drive a 2 inch diameter brass disk of a design recommended by Pilcher of Battelle Memorial Institute (20). Spray generation was obtained by feeding a liquid dye solution onto the disk center through a hypodermic needle. Spray classification was obtained by removing the unwanted satellites with a system similiar to that shown in Figure 13 and described below. Due to mechanical problems this generator produced a satisfactory aerosol at only a few operating conditions.

The developed generator is described below and shown in Figures 13, 15, and 16. Although this generator has been used for over a year to produce satisfactory aerosols it can be further improved mechanically. For this reason details are not given except where duplication is essential to successful operation.

Heart of the generator is a 2 inch diameter stainless steel disk driven by a high speed air motor. The air motor is mounted in a vibration isolating sponge rubber block 13 (Figure 16), mounted on a channel iron cross member 14 . The cross member 14 is



(A) RUBBER BULB
(B) HIGH VOLTAGE TRANSFORMER
(C) SATELLITE DISCHARGE
(D) SECONDARY BLOWER
(E) SATELLITE FILTER
(F) AIRMOTOR AIR DISCHARGE
(G) SATELLITE REMOVAL FUNNEL
(H) AIRLINE FILTER
(I) DRIER
(J) PRESSURE REGULATOR
(K) AIRLINE OILER
(L) CONSTANT HEAD LIQUID RESERVOIR
(M) LIQUID FILTER
(N) TWO WAY STOPCOCK
(O) NEEDLE VALVE
(P) PRIMARY AEROSOL DISCHARGE
(Q) IONIZER
(R) PRESSURE REGULATOR
(S) HYPODERMIC NEEDLE
(T) ORIFICE PLATE
(U) VOLTMETER
(V) AIRMOTOR
(W) INTAKE AIR FILTER
(X) MAIN BLOWER

Figure 13. Schematic of air flow and liquid feed system

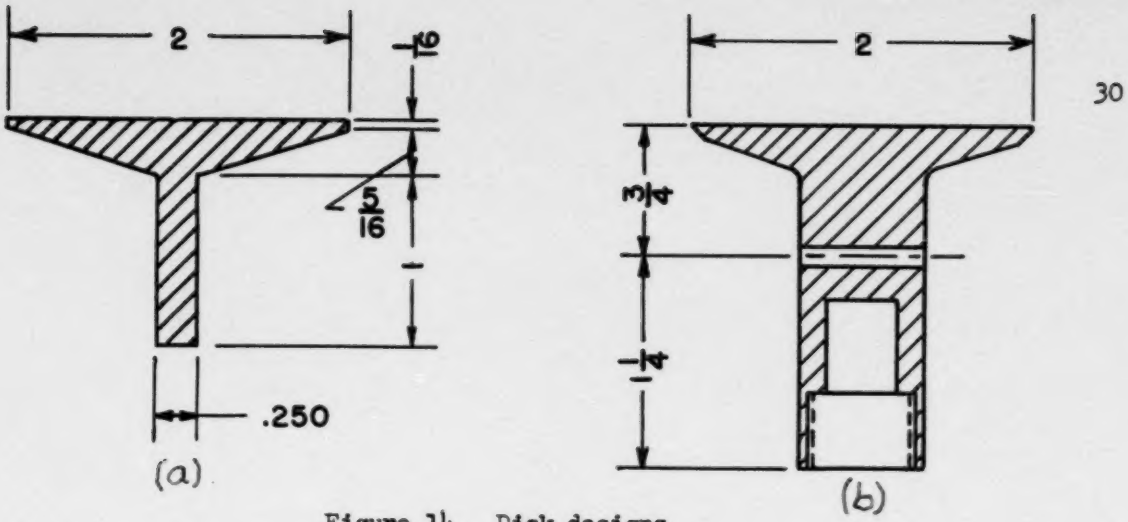


Figure 14. Disk designs

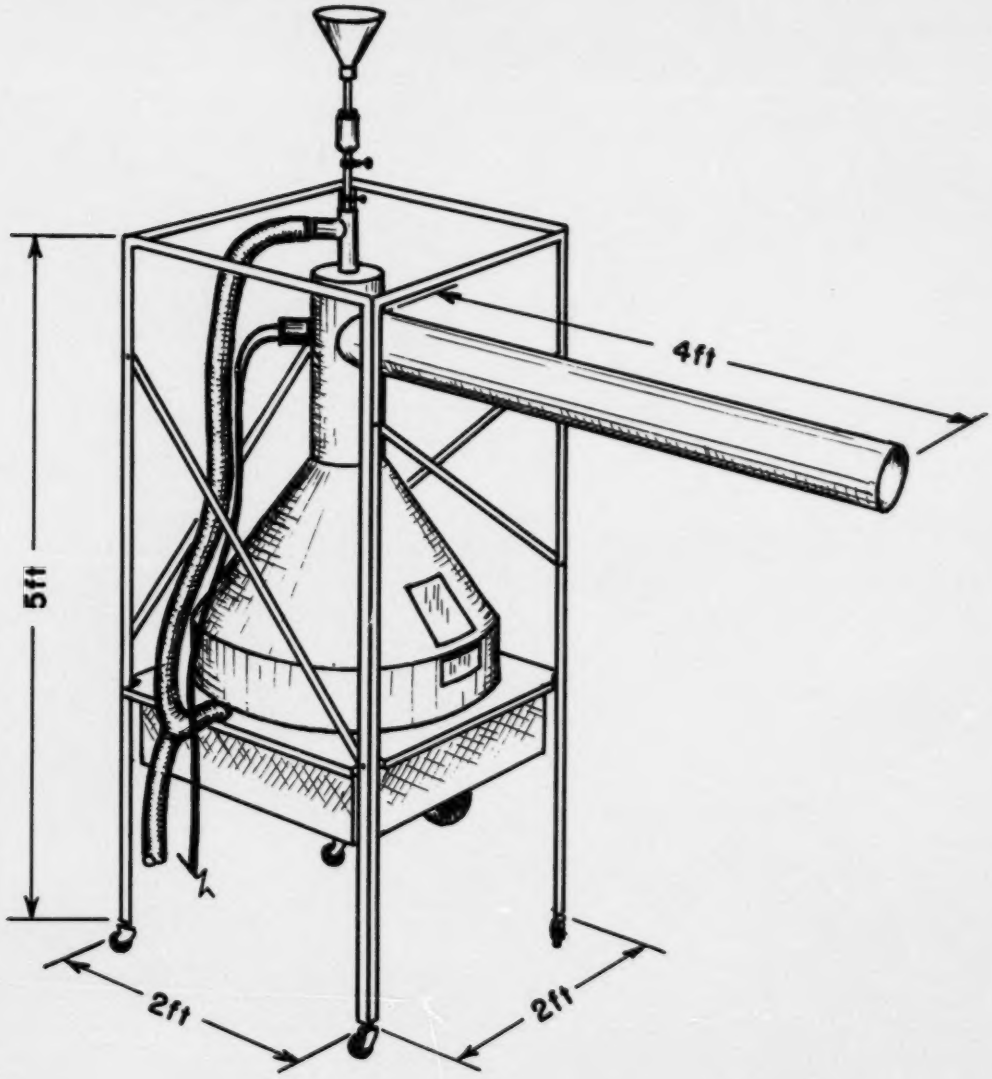


Figure 15. Sketch of spinning disk generator

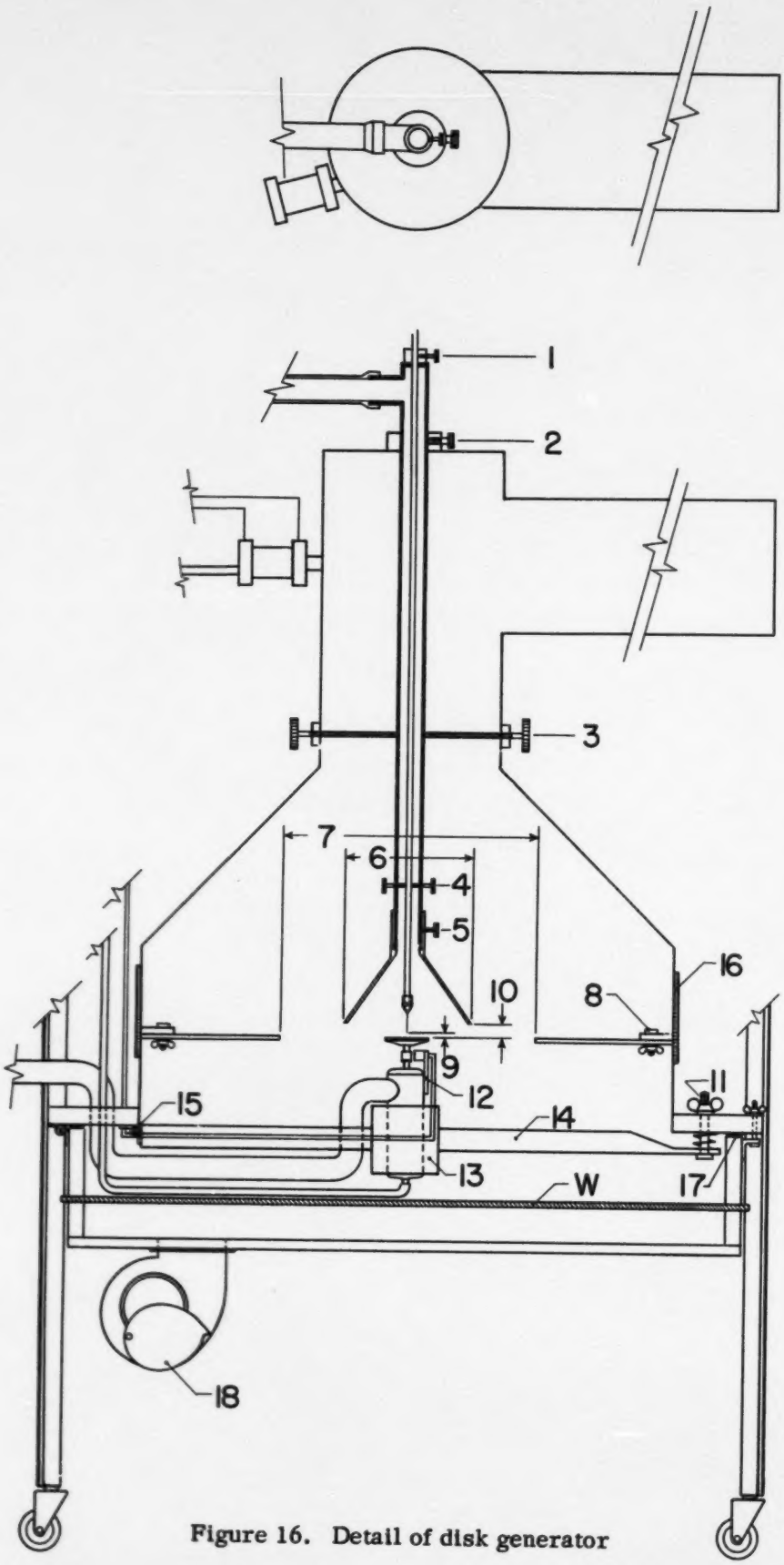


Figure 16. Detail of disk generator

Nomenclature for Figure 16

1	Hypodermic needle vertical adjustment clamp
2	Satellite funnel vertical adjustment clamp
3	3 satellite funnel horizontal positioning screws
4	3 hypodermic needle horizontal positioning screws
5	Satellite funnel locking screw
6	Satellite funnel diameter
7	Orifice plate diameter
8	Orifice plate positioning screws
9	Hypodermic needle to disk distance
10	Hypodermic needle to funnel distance
11	Disk vertical adjustment screw
12	Speed sensing element
13	Sponge rubber mounting block
14	Supporting frame
15	Hinge
16	Window
W	Filter and supporting screen
17	Foam rubber
18	Air flow damper

hinged 15 at one end and fastened by an adjusting screw and spring 11 at the other so that the motor can be raised or lowered to adjust the needle to disk spacing 9 . Compressed air for the motor passes through a drier I (Figure 13), a good quality air line filter H , a pressure regulator J and an air line oiler K if reasonable bearing life is to be obtained.

Dye solution is fed to the disk from a constant head reservoir L through a liquid filter M , a two way stopcock N , a needle valve O , and a hypodermic needle S (Figure 13). The two way stopcock and rubber bulb A , are provided so that the system may be purged of air by drawing dye solution up through the system.

The primary droplets thrown outward from the disk are carried upward by the flow of prefiltered air issuing from interchangeable orifice plate T . The prefilter W , consists of four square feet of Owens Corning PF 105 glass media. The two associated blowers, each rated at 1 inch water gage and at 140 c.f.m., and prefilter are held in a frame hinged at the rear so that it can be swung downward for access to the air motor. The evaporating droplets carried with the main airstream are mixed with ions provided by ionizer Q and leave through the aerosol discharge tube P.

Satellite droplets are carried upward inside interchangeable funnel G to filter E by an airstream provided by blower D.

Both the orifice plate T and funnel G are removable so that the appropriate size can be installed for each droplet size range generated. Funnel and orifice diameter as a function of air motor speed are given in Table III.

For convenience all of the above components are mounted on a 2 -foot square angle iron frame on castors, Figure 15. Components such as the air motor, funnel, orifice plate, feed system ionizer, etc. were made easily removable for cleaning because some aerosol loss in the generator is unavoidable.

1. Air flow system - A schematic of the air flow system is shown in Figure 13. This system provides for: regulation and filtration of intake air, uniform upward air velocity, interchangeable satellite removal funnel and orifice plate, and regulation and filtration of satellite removal air flow.

Aerosol discharge air varies from 40 to 100 c.f.m. while satellite air flow varies from 15 to 18 c.f.m. The 40 c.f.m. air flow is used when generating large droplets to increase the time for evaporation and decrease the loss due to particle impaction within the generator. Good separation of the fine spray obtained at high disk speeds requires high upward air velocities due to the outward air velocity induced by the disk and the relatively short stopping distances of the fine droplets. Different size orifices are used at various disk speeds to control upward air velocity at the point of spray separation.

At low disk speeds (10,000 R.P.M.) a few very large droplets are sometimes generated. May (16) noted the appearance of these large droplets at lower speeds but did not give an explanation for their existance. These few large droplets travel beyond the edge of the orifice plate and impact on the orifice plate or outer funnel.

Particle agglomeration has been observed only when generating very highly charged small particles at low air flow rates. Agglom-

eration was reduced by increasing the air flow.

Regulation of the air flow is obtained with dampers on the blower intakes. Intake air is passed through a high efficiency glass filter mat to remove air-borne dust and to provide the uniform upward air velocity necessary for good droplet classification.

Fixed dimensions of the air flow system are shown in Figure 15 while variable dimensions, such as orifice and funnel diameter, are tabulated in Table III as a function of the disk speed.

2. Liquid feed system - The liquid feed system shown in Figure 13 consists of a liquid reservoir, constant head reservoir, liquid filter, three-way valve, rubber suction bulb for drawing liquid up through the system, flow regulating valve, tubing and hypodermic needle.

By means of a 1/16 inch needle valve 0 the liquid flow can be regulated between 0.5 and 20 c.c./min. The filter has been found necessary to prevent plugging of the needle. A needle to disk spacing of about 0.01 inch is used to make sure that the liquid flows smoothly rather than drips onto the surface. Metal tubing with a hypodermic needle adaptor on the bottom or glass tubing with a finely drawn tip has been used successfully to feed the liquid. Optimum liquid feed rate is between 2 and 4 cm^3/sec. although higher flow rates have been used. Optimum flow rate increases with decreasing disk speed.

High concentrations of methylene blue dye tend to coat the metal surfaces of the feed system so that when low dye concentrations are used, careful cleaning is necessary to prevent readsorption of the dye. This trouble was not experienced when using uranine dye alone.

A future redesign of the spinning disk generator contemplates a simpler feed system consisting of only a variable head supply, connecting tubing and a hypodermic needle.

Most of the evaluation work was done using methylene blue dye in 95% ethyl plus 5% methyl alcohol at concentrations ranging from 5×10^{-5} to 3×10^{-3} parts by weight of dye because consistently good results could be obtained. Aerosol quality at somewhat higher and lower concentrations, although usable, was not as good.

Dye concentrations over 3×10^{-3} parts by weight of methylene blue may form crystalline deposits on the disk surface which destroy the aerosol homogeneity after a short operating time. This difficulty has not been experienced with uranine dye. All of the work to date has been done with alcohol solutions because they wet the metal disk surfaces. Water solutions could be used if the metal surfaces were treated by the process described by May (16), or if a glass disk surface were used.

So far it has not been possible to generate satisfactory pure uranine aerosols with methyl or ethyl alcohol as the solvent. Satisfactory particles of pure uranine have been obtained by adding demineralized water to the alcohol and/or by using a mixture of methylene blue and uranine dye in alcohol.

3. Air motor and disk design - An examination of equation (3)

$$d = \frac{K}{\omega}\sqrt{\frac{\tau}{\rho D}} \qquad (3)$$

shows that the droplet size and hence the minimum solid particle which can be generated is inversely proportional to the disk speed and to the square root of the disk diameter. High disk speeds are

most easily obtained with air driven motors. May (16) obtained speeds of up to 240,000 R.P.M. by using a free floating air driven top. However such tops are tricky to operate and have not been constructed larger than an inch in diameter.

Relatively inexpensive ($100) air driven grinders rated at about 75,000 to 85,000 R.P.M. at 90 psig. are available and have been used by Battelle (20), Harvard (8) and in this study. By careful balancing Battelle has obtained speeds of 150,000 R.P.M. Speeds of 85,000 R.P.M. with a 2 inch disk are normally all that can be expected.

Two different makes of motors have been used. An Aro Model 7335-A motor rated at 85,000 R.P.M. was used originally with a disk of the design shown in Figure 14-b. The Aro motor was accidentally damaged and replaced with a Keller Die Grinder size 30 A-7 rated at 75,000 R.P.M. at 90 psig. The disk design was changed to that shown in Figure 14-a. When new, the Keller motor ran at about 70,000 R.P.M. but as the bearings wore and were replaced, the maximum speed fell to about 55,000 R.P.M.

Both motors require clean filtered air. In addition an air line oiler should be used with the Keller motor. The exhaust air is discharged as a jet in the direction of the motor shaft. This air jet creates turbulence and must be collected by a manifold and removed since it makes separation of the satellite and main droplets difficult. Due to differences in turbine design, the Aro motor is more stable at lower speeds (6,000 to 15,000 R.P.M.) ~~that~~ than the Keller motor.

Control of the particle size requires that the disk speed be regulated during aerosol generation. Calibration of speed versus

applied air pressure is not satisfactory. Two simple speed measurement methods have been used with fair success. The first used a 1/8 inch diameter bar magnet embedded in a hole perpendicular to the disk axis (Figure 14-b) and a magnetic earphone. The voltage produced by the earphone was calibrated against the speed measured by an electronic pulse counter. The second approach used with the disk shown in Figure 14-a was to place a miniature magnetic earphone next to the hex-nut of the air motor collet. The latter was quite satisfactory except that slight shifting of the earphone due to the vibration of the motor required frequent recalibration. It has been found necessary to mount the air motor in a block of sponge rubber to reduce the effects of air motor vibration. This may be unnecessary with very careful motor balancing.

Factors which must be considered in the design of the disk are adequate strength, power available, liquid wetability, edge uniformity, liquid feed rate desired, and the minimum droplet size desired.

A two inch disk has been used rather than the 1 inch disk used by others because this decreases the minimum particle size obtainable at a given speed and also increases the optimum feed rate and aerosol output.

The maximum stress at the center of a thin disk of constant thickness is given by (21):

$$S_{max} = \frac{3+\mu}{8} \frac{\rho \omega^2 \left(\frac{D}{2}\right)^2}{g} \qquad (4)$$

where:
- S_{max} = maximum stress
- ρ = disk density
- ω = angular velocity - radians/sec.
- D = disk diameter
- μ = Poisson's ratio
- g = gravity constant

If a 2 inch diameter steel disk is run at 100,000 R.P.M. the maximum stress is calculated from equation (4) to be 30,000 lbs/in^2. This illustrates that caution must be used in design and operation of a high speed disk.

At disk speeds of around 240,000 R.P.M., 6 micron droplets were produced by May (16) but the problems encountered make this impractical. At speeds above 150,000 R.P.M. the constant in equation (3) increases due to slip between the disk surface and the liquid, cancelling much of the particle size reduction obtained at high speeds.

Optimum liquid feed rate and therefore, droplet number, increases with increasing disk diameter and decreasing disk speed. Equation (3) requires that $\omega D^{\frac{1}{2}}$ be constant for a given droplet size and liquid; therefore, more droplets of a given size are generated when using a slower speed and larger disk.

Important disk properties for satisfactory operation are very low ecentricity, a relatively smooth flat surface, a surface perpendicular to the axis of rotation and a very uniform edge profile. Absolute edge sharpness is not important, but the edge profile uniformity is very important in generating a homogeneous aerosol. A square edge profile was used because it was easy to machine and grind.

4. Particle charge - An electrically neutral liquid droplet can become a highly charged particle through the process of evaporation. It has been found that when a liquid droplet with a low initial concentration of non-volatile material is evaporated, the electrical charge on the resulting particle can approach the maxi-

mum equilibrium charge. The following example is an illustration that this charge can be a significant factor in the use of the aerosol for filter testing. Collection efficiency of a standard felt filter at 42 fpm face velocity increased from 20 percent with a neutral aerosol to 80 percent with a highly charged 1.4 micron aerosol.

Most of the studies of the charge on particles generated by the spinning disk have been made using the charged particle separator shown in Figure 10. More recently an electrostatic precipitator of the type described by Langer (22) has been used to obtain precise measurement of the particle charge. Charge neutralization is obtained using the ion generator described in Part III. The location of the ion generator in the spinning disk generator flow system is shown in Figures 13 and 16.

It has been observed when generating uranine-methylene blue particles, that if the droplets completely evaporate before they are mixed with the ions, the high charge may result in ellipsoidal or teardrop shaped particles.

The following data obtained with the Langer type precipitator illustrates the effectiveness of the charge neutralizer. With the generator producing 2.3 micron solid particles from a 6.3×10^{-4} parts by volume solution of one half uranine and one half methylene blue dye in methyl alcohol, the median particle charge was 630 electron units of positive charge with the ion generator off and about 5 units with it on. Thus the particle discharging system reduced the median charge from about 20% of the maximum equilibrium charge to less than 0.2%. The aerosol generator with the charge

neutralizer in operation may be considered to produce an electrically neutral aerosol.

E. Aerosol Generator Operation

The variables involved in operating the generator are tabulated in Table III as a function of motor speed. The Table was made up by listing the flow values, etc., used to obtain satisfactory results at different operating conditions. The orifice diameters listed may be used over a limited range of speeds on either side of the tabulated values.

A given particle size can of course be produced with various combinations of disk speed and dye concentration. Except when the maximum generation rate or the smallest particle size is needed, a medium dye concentration and the appropriate speed will usually be found to produce the most satisfactory aerosol and result in the most stable generator operation. Once the disk speed is selected, the other generator operating conditions may be obtained from Table III.

The operating procedure is briefly as follows:

1) Install needle, funnel and orifice plate
2) Set needle projection distance
3) Center needle in funnel
4) Set funnel vertical position
5) Fill liquid reservoir and flush out feed system with the dye concentration to be used
6) Set liquid flow rate
7) Start disk, satellite air blower and main air blower
8) Center needle and funnel above disk

9) Adjust needle to disk space

10) Start liquid feed

11) Turn on ionizer air

12) Turn on ionizer voltage

13) Adjust disk speed, air flows, needle centering, etc., as necessary

After the generator has been running satisfactorily for several minutes, an aerosol sample should be taken to check the particle size and quality. Even if previous runs have produced consistently good results, a check is usually desirable.

A homogeneous, mono-dispersed, solid, neutral aerosol should now be generated.

F. Aerosol Quality

The homogeneity of the aerosol produced was found to vary with the operating conditions such as dye, dye concentration and solvent. Under the conditions given in Table III, the poorest aerosols were found to have a σ_g of about 1.15. Under most conditions a σ_g of 1.05 was obtained.

Particle shape varied somewhat with dye concentration and the dye-solvent combination used. Very spherical particles were produced with methylene blue and ethyl alcohol, and less spherical, but satisfactory, particles with a uranine-methylene blue-alcohol mixture. Very elongated or teardrop shaped particles were often observed with low dye concentrations if the ion generator was turned off or was not operating properly.

There is very little aerosol aggregation at the generator outlet. However, up to 10% aggregation resulted when the undiluted

aerosol was allowed to flow slowly down the test duct in which the aerosol samplers were located. Aggregation was greatly reduced by diluting the aerosol by a factor of four or so at the test duct inlet.

G. Improvement of the Spinning Disk Aerosol Generator

Experience with the generator described here has suggested some further improvements to increase operating convenience and stability of operation.

Since the air motor is unstable at speeds near 10,000 R.P.M. it would be desirable to use a low speed air motor or electric motor at low speeds to generate large droplet sizes and to use a high speed air motor to generate small droplet sizes. It appears practical to generate all particle sizes between 0.4 and 20 microns with two disk speeds by varying the dye concentrations used between 10^{-5} and 10^{-2} parts by volume. The first unit would consist of a 10,000 R.P.M. air or electric motor, a 4 inch disk and its associated orifice, funnel and feed needle. The second unit would consist of a 75,000 R.P.M. high speed air motor, a 2 inch disk and associated equipment. The low speed unit could generate particles from about 2.5 to 20 microns and the high speed unit from about 0.4 to 3 microns. Once adjusted for optimum performance, each unit should be capable of generating aerosols of quite constant size with less effort than is now required.

Table III

Operating conditions at which spinning disk has been used[a]

Air motor R.P.M.	70,000	45,000	30,000	20,000	12,000
Main droplet diameter - microns (±10%)	19	28	41	60	100
Dye concentration by weight - gram/gram	5×10^{-5} to 3×10^{-3}	1×10^{-5} to 3×10^{-3}	5×10^{-5} to 3×10^{-3}	5×10^{-5} to 3×10^{-3}	5×10^{-5} to 3×10^{-3}
Solid particle diameter - microns	0.6-2.4	0.6-3.5	1.3-5.1	1.9-7.5	3.2-12
Discharge air flow - c.f.m.	100	100	70	50	40 to 50
Orifice diameter - inches	6	6	7½	9	15
Satellite air flow - c.f.m.	15	15	15	16	18
Satellite funnel diameter - inches	2½	3	4	5	6
Liquid feed rate - c.c./min. (±20%)	2½	3	3	3½	4
Feed needle size - number	22	22	22	19	19
Particle generation rate - particles/min (±20%)	350×10^6	130×10^6	40×10^6	15×10^6	3×10^6
Projection of the hypodermic needle below the satellite funnel - inches	1/16	3/32	1/8	3/16	3/16
K in equation (3) (±10%)	5.6	-	-	-	5.0

(a) Data obtained using Methylene Blue dye in Alcohol. Disk diameter = 4.65 cm.

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